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Closed Loop PMI Driven Dimensional Quality Lifecycle Management Approach for Smart Manufacturing System

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Abstract

In order to devise, build and control a self-organizing smart manufacturing system for certain modular product architecture to support mass personalization, it is essential to accurately predict quality and performance of the manufacturing processes among others. Dimensional quality issues have been widely studied to understand causes of variations of product manufacturing qualities and various point solutions such as Variation Simulation Analysis (VSA), Dimensional Planning and Validation (DPV) and Coordinate Measurement Machine (CMM) have been adopted. However, dimensional quality issues will never be sufficiently addressed unless all major causes during lifecycle are identified and managed. This research provides a holistic approach to build a closed loop Plan-Do-Check-Act (PDCA) lifecycle from dimensional design, planning and inspections via a unique data repository which can accurately, effectively and smartly carry on and reuse Product and Manufacturing Information (PMI) during product lifecycle time. The new approach integrates universal semantic model using Feature Associated Geometric Dimensioning and Tolerancing (GD&T) Information Reuse, consistently stated Dimensional Quality Lifecycle and it captures, identifies and reuses 3D geometry characteristics and their associated GD&T information of the semantic model. The approach also establishes a closed loop quality lifecycle management system incorporating GD&T Design and Validation, Inspection Planning and Validation, Measurement Data Analysis and Reporting, and GD&T Design and Validation. The new approach has been applied by a functional failure study for an industrial product platform. It proves that the holistic approach can ensure single version of truth, enforce reusable technical specifications, eliminate silos among different process steps, and enable design for manufacturing to achieve optimal cost/performance balance at very early stage. Furthermore, the paper suggests future research directions of dimensional quality management system advancement based on smart PMI technologies augmented by Internet of Things, VR/AR and Cyber Physical Systems.

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Keywords: Model-based Definition (MBD); Product and Manufacturing Information (PMI); Dimensional Quality Lifecycle; Unique Data Source; Feature Associated GD&T Information Reuse; Plan, Do, Check, Action (PDCA); Uniformed Representation Model of Tolerance Stackup

1. Introduction

Manufacturing dimensional variations result in assembly difficulties, functional non-conformance and appearance quality issues. It requires a system engineering method and concurrent engineering approach to manage manufacturing variations throughout product development lifecycle in controlled manner by collaborative work by product engineering, manufacturing engineering, quality assurance and suppliers using various engineering tools. A lot of research effort is spent on how to appropriately define a data backbone to make Product and Manufacturing Information (PMI) flow from upstream to downstream processes, to develop some automatic programs for reusing the PMIs in various steps in order to efficiently integrate three key dimensional engineering activities including Geometric Dimensioning and Tolerancing (GD&T) Design and

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Validation, Inspection Planning and Validation, and Measurement Data Analysis and Reporting in order to balance functional product performance and manufacturability to satisfy individualized customer configurations at affordable cost.

Many scholars have studied Design For X (DFx) [1, 2], the definition of GD&T semantic model [3, 4, 5, 6, 7, 8, 9, 10], GD&T Design and Optimization [11, 12, 13], Inspection and Measurement [14, 15], Variation Management System [16,17,18] and various stages of R&D processes and raised some concepts such as total tolerance management, Design for Dimensional Control (DDC), created structured, parametric and interactive rule-based knowledge models, developed feature-based manufacturing technologies to drive interoperability among processes with an purpose of optimal design quality and manufacturing cost. Although such researches greatly advanced manufacturing variation control technologies, all are mainly point solutions and big improvement areas exist in closed-loop integrations including the following:

- Lack single unique data sources to facilitate seamless flow of PMI
- Inconsistent standard for Feature Associated information reuse
- Lack closed-loop control for variance management system
- Lack unified manufacturing process representation model to link three key dimensional management activities including design, planning and measurement

In order to solve the aforementioned problems, this research proposes to use Model Based Definition (MBD) to define GD&T semantic model as a unique source of data, to enhance 3D geometry annotation by automating feature capture, recognition and reuse to realize PMI driven dimensional management activities including GD&T Design and Validation, Inspection Planning and Validation, and Measurement Data Analysis and Reporting. Those three key activities plus 3D uniformed representation model of tolerance "stackup" forms a closed-loop PDCA system so that islands of information are eliminated and continuous design for manufacturing can be realized.

Existing manufacturing variances management and control theories, methods and tools are reviewed in chapter 2. A new holistic approach is proposed in chapter 3 and technical implementation options for three key dimensional management activities will be discussed. An industrial application concerning functional failures is reviewed in chapter 4. A conclusion is made and future research directions concerning the topic are discussed in chapter 5.

Nomenclature

PMI	Product and Manufacturing Information;
GD&T	Geometric Dimensioning and Tolerancing;
DQLM	Dimensional Quality Lifecycle Management;
DFx	Design for X;
DFA	Design for Assembly;
DFM	Design for Manufacture;
CAT	Computer Aided Tolerancing;
MBD	Model Based Definition;
PDCA	Plan, Do, Check, Action;
CMM	Coordinate Measurement Machine;
KPC	Key Product Character;
PCA	Principle Component Analysis;
VSA	Variation Simulation Analysis;
DMIS	Dimensional Measurement Interface Standard;
BOP	Bill of Planning;
BOR	Bill of Resources;
DPV	Dimension Planning and Validation;
VR/AR	Virtual Reality/Augmented Reality.

2. Existing Approaches

From our study and practices in industries including automotive and transportation, aerospace and defense, high technology and electronics, the following mainstream manufacturing variance control techniques are classified.

2.1. DFx Approach for Manufacturing Variation Control

Dimensional quality is both made and devised. Adopting concurrent engineering concept in design for manufacturing is early inception of full lifecycle quality management. Paul G. Leaney, in his DFx Concurrent Engineering defined DDC technique and developed a methodology and toolbox to control manufacturing variances to some extend [1]. In order to minimize number of design-manufacturing iterations in serial engineering, Ali K. Kamrani and Sa'ed M. Salhieh raised the idea of reviewing Design for Manufacture and Assembly [2] including variation control.

2.2. Information Carrier and Reuse Approach for Manufacturing Variation Control

Ali K. Kamrani and Emad Abouel used 2D GD&T drawings to communicate among design, manufacturing and test [3]. The information carrier is 2D drawing. With adoption of 3D models, GD&T information can be represented in 3D CAD model. Zhengshu Shen, Jami J. Shah and Joseph K. Davidson defined a super constraint-tolerance-feature-graph (SCTF-Graph) GD&T semantic model sufficiently satisfies information needed by commonly used tolerance analysis methods [5]. R. I. M. Young, O. Canciglieri-Jnr and C. A. Costa studied a data model to facilitate interoperability between functional design and manufacturability at product design stage [4]. Similarly, José Vicente Abellán-Nebot devised two 3D digital variable models, from product quality and manufacturability perspectives respectively, for multi-station machining system to predict part manufacturing dimensional quality and to generate robust process plans so that both labour hours and downstream quality risks can be minimized. [7].

Feature reuse techniques make it possible for information carriers to be used across processes. Jian Gao, De Tao Zheng and Nabil Gindy stated that the key to realizing interoperability of features are how to recognize and validate GD&T features and studied robust techniques to ensure completeness of features, which can be used from transferring design features to manufacturing features during process planning[6]. László Horváth, Imre J. Rudas and János F. Bitó used Generic Petri nets to represent process variables in unified manufacturing model and studied feature-driven part and its associated manufacturing model to test interdependency between part model changes and manufacturing process models [8]. Rui Huang, Shusheng Zhang and Xiaoliang Bai devised a machining features based multi-level structuralized MBD model to capture descriptive information, detailed feature interactive information, machining semantic information in order to drive manufacturing knowledge reuse [10]. Sungdo Ha, Inshik Hwang and Kwanbok Lee developed a technique to annotate GD&T into 3D digital model to drive optimization of production process selection and CMM inspection paths so that GD&T information are easily accessible among designer, process planners, field operators and QA personnel, resulting in better manufacturing quality [9].

2.3. Integrated Design and Inspection Approach for Manufacturing Variation Control

From dimensional design validation perspective, Basilio Ramos Barbero, Jorge Pérez Azcona and Jorge González Pérez used 3D CAT system, dimensional hierarchization matrix and optimization algorithm, and developed tolerance analysis and optimization methodology [11]. Wilma Polini set tolerance values for each part in an assembly based on tolerance standard system and associated best practices via concurrent tolerance design technique [12]. From dimensional quality inspection perspective, Yaoyao Zhao, Robert Brown and Thomas R. Kramer developed a typical dimensional measurement system including four key processes including product definition, measurement process plan, measurement process execution and quality data analytics [13], and argued that 3D product CAD model annotation shall consider ease of reuse for follow-on process planning, manufacturing process and quality assurance activities [15]. Ali Kamrani, Emad Abouel Nasr and Abdulrahman Al-Ahmari build inspection plan based on feature capture and recognition techniques such as clustering algorithm, graphical method, artificial neural networks and Measuring Point generating algorithm to improve CMM program efficiency [14].

2.4. Variation/Tolerance Management System Approach for Manufacturing Variation Control

Considering Variation/Tolerance Management System, Alain Etienne, Jean-Yves Dantan and Jawad Qureshi used genetic algorithm and constraint satisfaction algorithm and developed Key Characters-based tolerance allocation and manufacturing process selection technique to derive an optimal coefficient for balancing product function (quality) and manufacturability (cost) and finally used Monte Carlo simulated product quality to assess manufacturing process selection impact [16]. Rainer Müller, Martin Esser and Christian Janßen developed an idea of total tolerance management and applied it to realize high quality low cost assembly process [17]. Spencer Graves and Søren Bisgaard believe that a tolerance management system should consist of planning, control and improvements sub-systems and described each of the functions [18]. Alexander P. Morgan, John A. Cafeo and Diane I. Gibbons argues that dimensional management is key to mechanical structure's quality and use Case-Based Reasoning technique via case structure and matching ontology to build context and generic language to adjust process, monitoring and problem handling to respond to changes in environment and materials [19].

The existing manufacturing variance control techniques vary in their idea, method and tools but the following limits do exist:

- Inconsistent 3D model making it difficult for OEMs and their suppliers to exchange information freely
- Multiple Feature Associated reusable standards make GD&Ts impossible to freely flow from design to test and/or design to manufacturing inside a company
- Lack closed-loop feedback in variance management system and manufacturing quality data fluctuation is difficult to be delivered to designer on timely and accurate manner to drive optimal engineering changes
- Only existing digital 3D model cannot fully support DFx

3. Proposed DQLM Methodology

Thanks to MBD technology advancement, CAD models gradually evolve from pure geometries to integrated representations of product lifecycle data and most product-related structured data can be embedded in CAD models [20]. GD&T semantic models as unique source of data can possibly be built using Feature Associated GD&T 3D annotation and reuse techniques. By using automation technologies in capturing, recognizing and reusing GD&T semantic model, PMI can drive three key dimensional management activities including GD&T Design and Validation, Inspection Planning and Validation, and Measurement Data Analysis and Reporting. As illustrated in the Figure 1, closed-loop feedback control can be realized via uniformed representation model of tolerance "stackup" built in the activity GD&T Design and Validation. All three activities will be elaborated in the following sections.

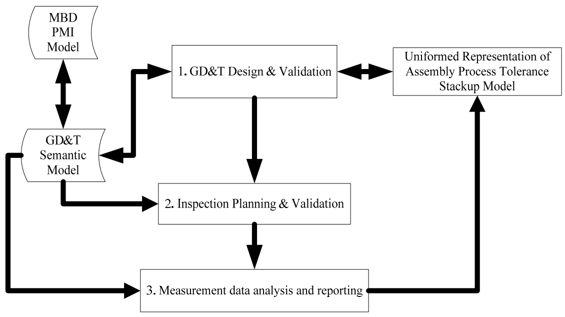

Fig. 1. Part and Manufacturing Information Driven Dimensional Quality Lifecycle Closed loop Management System

3.1. GD&T Design and Validation

GD&T Design and Validation is the beginning and the end of closed-loop dimensional quality lifecycle management. GD&T is a globally accepted standard engineering language including tolerance principle, boundary condition, symbol grammar, baseline system and definition and statements of 14 geometric tolerances. GD&T Design and Validation defines interrelation between part and component geometry features and the functional interfaces with corresponding assembly to describe part/component GD&T requirements, uses uniformed representation model of tolerance "stackup" to validate and optimize design and process in order to optimally balance product function (quality) and manufacturability (cost). The output of this activity is GD&T information for DFx.

Because GD&T engineering language can help engineers in various departments to accurately communicate technical specifications and requirements for manufacturing and inspections concerning product dimensions and tolerances, Feature Associated 3D CAD model fully annotated with GD&T information can serve as unique source of data for MBD PMI to make a GD&T semantic model. By capturing, recognizing and reusing geometric features annotated, a uniformed representation model of tolerance "stackup" can use those features attached to the GD&T information to build assembly function. With such a function, using Monte Carlo algorithm to simulate product manufacturing and assembly process, dimensional quality and variations can be predicated and contributing factors to the variations can be analysed to unveil how part/component manufacturing variances impact various KPCs of the product in order to analyse and assess if certain part/component, process and fixtures/tools can meet predefined design goals.

By uniformed representation model of tolerance "stackup" and analysis based on GD&T semantic model, PMI driven GD&T Design and Validation can validate possible dimensional problems and provide proposals for design and process optimization and update GD&T semantic model so that adjacent processes can gain latest GD&T instructions so that collaborative product design can be achieved to reduce design changes and costs associated in manufacturing and inspections and to shorten time to market.

3.2. Inspection Planning and Validation

During process planning stage in a product development process, dimensional quality inspection plans and work instructions are required to be developed for each of every part, component and final product. The plans include inspection objects, scope, method, tool, frequency, spec, condition, environment and etc. Inspection Planning and Validation activity is expected to maximally reuse the MBD PMI carried by the GD&T semantic model, to create work instructions for manual inspections such as First Part Approval Inspection and/or CMM inspection execution programs for automatic inspections. In addition, inspection process must be validated. Because of MBD PMI as unique sources of information, costly inspection equipment utilization rate can be increased and the results can be made sense by visualization and comparisons.

By doing so, PMI driven Inspection Planning and Validation activity can validate and optimize inspection process so that time for measurement is condensed. In addition, MBD PMI can be automatically updated according to design changes introduced by GD&T Design and Validation activity so that single version of truth is ensured and risks associated with data inconsistency are minimized.

3.3. Measurement Data Analysis and Reporting

During product ramp-up and operational management, manufacturing qualities problems such as assembly difficulties, malfunction, bad look and feel and etc. are reported. By comparing the inspection results from Inspection Planning and Validation activity with GD&T semantic model and using advanced SPC tools, root causes can be identified. Such analysis results are sent back to GD&T Design and Validation to further optimize design and process plan to close the loop. Various levels of dimensional quality fluctuation monitoring reports are circulated to share with relevant departments to support TQM initiatives.

In addition, the analysis reports can be circulated to related departments and users as a TQM initiative.

4. An Industrial Application

To prove the concept and to validate the methods and tools, a coffee machine malfunction issues have been studied using closed-loop PMI-driven dimensional management approach. The tools used include VSA™ [22] for GD&T Design and Validation, NX™ CMM [23] for Inspection Planning and Validation and DPV™ [24] for Measurement Data Analysis and Reporting.

The consumers reported that inconsistent coffee flavors occur frequently from a new model of coffee machines. According to preliminary analysis conducted by quality department, the possible cause is that distance gap between upper grinder and lower one cannot be controlled within set standard +/-0.5mm. GD&T Design and Validation activity was initiated and the analysis confirmed that top four KPCs to the 7.44% variance of the distance include four critical dimensions on the retainer. According to discussion with manufacturing department, top factor of 0.8mm surface profile can be improved to 0.5mm. Manufacturing Engineers performed inspection planning and validation against the four KPCs using CMM machines to measure all retainers provided by three vendors. Based on comparative analysis on variance against nominal values, one vendor was identified which consistently varied 1mm in the tools they employed. Accordingly the vendor was asked to improve their tools and their retainer KPC dimensional fluctuation reduced significantly and the quality issue of inconsistent flavors was solved. In aforementioned three activities accurately and efficiently formed a closed loop PDCA cycle using PMI-driven 3D Uniformed Representation Model of Tolerance Stackup, which is illustrated in below diagrams.

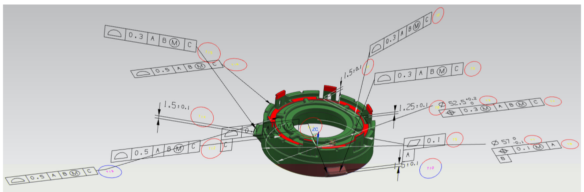

Fig. 2 The Coffee Machine Application - GD&T Semantic Model

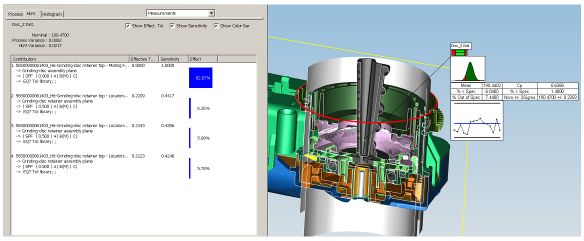

Fig 3 GD&T Design and Validation

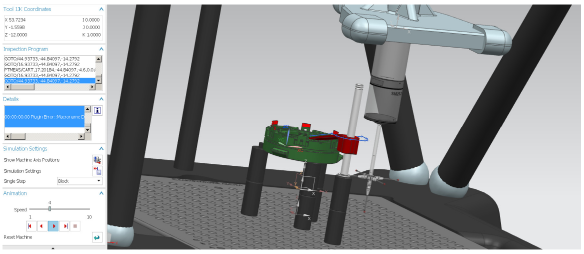

Fig 4 Inspection Planning & Validation

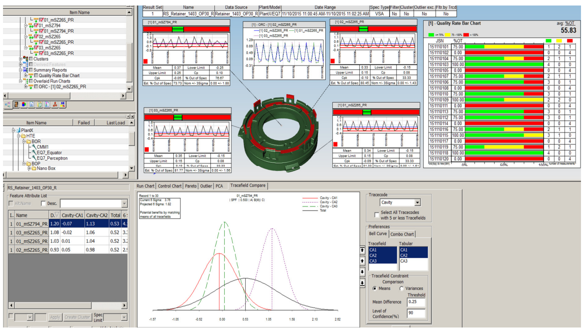

Fig 5 Measurement data Analysis and Reporting

The operational processes are documented as the following.

- Step one: Create GD&T sematic model in line with design intent and enter MBD PMI information for coffee machine part/components. Capture, recognize and reuse Feature Associated GD&T 3D annotation and use VSA^{TM} to build unified 3D uniformed representation model of tolerance "stack up" to identify top contributors to variation sources to the KPC which is the gap between the upper and lower grinder for this case, then validate, optimize and update PMI in GD&T sematic model. The four critical dimensions of the retainer are KPCs to the gap.
- Step two: By reusing PMI information confirmed by previous step, inspection path is automatically generated and virtually optimized by NX^{TM} CMM and DMIS compatible program is generated by the post build. Execute CMM inspection programs for the part and send the measurement results to DPV^{TM}.
- Step three: Comparing MBD PMI of top contributor and using DPV^{TM} to analyze measurement results, the root cause of KPC failure is that 0.8mm of surface profile is caused by the tools employed by a retainer vendor varied 1mm. Update the uniformed representation model of tolerance "stack up" in MBD PMI in step one and validate how much the root cause identified contributes to the gap KPC. Adjust the mold of retainer dimension in question and run mean shift what-if scenario driven by measurement data to calculate improved result of KPC. Update GD&T semantic model accordingly and close the loop.

5. Summary

The Closed Loop PMI Driven Dimensional Quality Lifecycle Management Approach for Smart Manufacturing System proposed by the article and validated by an industrial application employs MBD technique to define complete and reusable GD&T sematic model as a unique source of data, unified 3D GD&T annotation and uniformed representation model of tolerance "stackup" to drive GD&T Design and Validation, Inspection Planning and Validation through Measurement Data Analysis and Reporting then back to GD&T Design and Validation to close the loop. Such an approach ensures unique source of data and consistency of metadata standards, which can help a smart manufacturing system to optimally balance quality and manufacturability.

As the concept of smart manufacturing system or smart factory continue to evolve driven by latest developments in Internet of Things, VR/AR and Cyber Physical Systems, the implementation of the Closed Loop PMI Driven Dimensional Quality Lifecycle Management Approach can be enhanced.

- Adopt VR/AR in the closed-loop dimensional quality management system. Technicians may use body motion to create GD&T sematic model including PMI and use gestures to manipulate complex uniformed representation model of tolerance "stackup" and to perform GD&T Design and Validation, Inspection Planning and Validation and update MBD PMI model via VR/AR
- MBD PMI model may expand to incorporate Bill of Resources and Bill of Processes associated with manufacturing, assembly and inspection to allow direct access to inspection machines in digital environment
- Use Virtual Matching for manufacturing data to enhance immerse decision making experiences for engineers to

conduct numerous what-if analysis to take optimization of product design and process planning to next level

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References

[1] Paul G. Leaney. Design For Dimensional Control, in Design for X--Concurrent engineering imperatives(ed. G. Q. Huang). Springer Netherlands, 1996, pp 173-195.

[2] Ali K. Kamrani, Sa'ed M. Salhieh.Design for Manufacture and Assembly, in Product Design for Modularity. Springer US, 2002, pp 143-187.

[3] Ali K. Kamrani, Emad Abouel Nasr. Geometric Dimensioning and Tolerancing, in Engineering Design and Rapid Prototyping. Springer US, 2010, pp 313-338.

[4] R. I. M. Young, O. Canciglieri-Jnr, C. A. Costa. Information interactions in data model driven design for manufacture, in Globalization of Manufacturing in the Digital Communications Era of the 21st Century, Volume 4 of the series IFIP - The International Federation for Information Processing, Springer US, 1998, pp 313-324

[5] Zhengshu Shen, Jami J. Shah, Joseph K. Davidson. Analysis neutral data structure for GD&T, *Journal of Intelligent Manufacturing,* August 2008, Volume 19, Issue 4, pp 455-472.

[6]Jian Gao, De Tao Zheng, Nabil Gindy, Doug Clark. Extraction/conversion of geometric dimensions and tolerances for machining features, *The International Journal of Advanced Manufacturing Technology,* August 2005, Volume 26, Issue 4, pp 405-414.

[7] José Vicente Abellán-Nebot, Fernando Romero Subirón, Julio Serrano Mira. Manufacturing variation models in multi-station machining systems, *The International Journal of Advanced Manufacturing Technology,* January 2013, Volume 64, Issue 1, pp 63-83.

[8]László Horváth, Imre J. Rudas, János F. Bitó, Aniko Szakal.Feature Driven Associative Part and Machining Process Models, in *Knowledge and Technology Integration in Production and Services,*Volume 101 of the series *IFIP — The International Federation for Information Processing,* Springer US, 2002, pp 11-18.

[9] Sungdo Ha, Inshik Hwang, Kwanbok Lee, Hyung-Min Rho. Tolerance Representation Scheme for Integrated Cutting Process & Inspection Planning, in *Global Consistency of Tolerances*(ed. Fred van Houten, Hubert Kals), Springer Netherlands, 1999, pp 131-138

[10] Rui Huang, Shusheng Zhang, Xiaoliang Bai, Changhong Xu, Multi-level structuralized model-based definition model based on machining features for manufacturing reuse of mechanical parts, *The International Journal of Advanced Manufacturing Technology,* November 2014, Volume 75, Issue 5, pp 1035-1048

[11] Basilio Ramos Barbero, Jorge Pérez Azcona, Jorge González Pérez. A tolerance analysis and optimization methodology. The combined use of 3D CAT, a dimensional hierarchization matrix and an optimization algorithm, *The International Journal of Advanced Manufacturing Technology*,October 2015, Volume 81, Issue 1, pp 371-385

[12] Wilma Polini. Concurrent tolerance design, *Research in Engineering Design*, January 2016, Volume 27, Issue 1, pp 23-36.

[13] Yaoyao (Fiona) Zhao , Robert Brown, Thomas R. Kramer, Xun Xu. High-Level Dimensional Metrology Process Planning, in *Information Modeling for Interoperable Dimensional Metrology*. Springer London, 2011, pp 119-164.

[14] Ali Kamrani, Emad Abouel Nasr, Abdulrahman Al-Ahmari, Osama Abdulhameed, Syed Hammad Mian. Feature-based design approach for integrated CAD and computer-aided inspection planning, *The International Journal of Advanced Manufacturing Technology*, February 2015, Volume 76, Issue 9, pp 2159-2183.

[15]Yaoyao (Fiona) Zhao, Robert Brown, Thomas R. Kramer, Xun Xu. Product Definition and Dimensional Metrology Systems, in *Information Modeling for Interoperable Dimensional Metrology*, Springer London, 2011, pp 53-118

[16] Alain Etienne, Jean-Yves Dantan, Jawad Qureshi, Ali Siadat. Variation management by functional tolerance allocation and manufacturing process selection, International Journal on Interactive Design and Manufacturing (IJIDeM), October 2008, Volume 2, Issue 4, pp 207-218

[17]Rainer Müller, Martin Esser, Christian Janßen, Matthias Vette, Stefan Qu inders. Tolerance Management for Assembly – Not a Matter of Product Size, in Precision Assembly Technologies and Systems(ed. Svetan Ratchev), Volume 371 of the series IFIP Advances in Information and Communication Technology, Springer Berlin Heidelberg, 2012, pp 97-104

[18] Spencer Graves, Søren Bisgaard. Integrated Tolerance Management, in Global Consistency of Tolerances(ed. Fred van Houten, Hubert Kals), Springer Netherlands, 1999, pp 385-394

[19]Alexander P. Morgan, John A. Cafeo, Diane I. Gibbons, Ronald M. Lesp erance, Gülcin H. Sengir, Andrea M. Simon. CBR for Dimensional Management in a Manufacturing Plant, in Case-Based Reasoning Research and Development(ed. David W. Aha, Ian Watson), Volume 2080 of the series Lecture Notes in Computer Science, Springer Berlin Heidelberg, 2001, pp 597-610

[20] M. Alemanni, F. Destefanis, E. Vezzetti, Model-based definition design in the product lifecycle management scenario*, The International Journal of Advanced Manufacturing Technology,* January 2011, Volume 52, Issue 1, pp 1-14

[21] ASME, Standard. (2009). Dimensioning and Tolerancing, ASME Y14.5M-2009. New York: American Society of Mechanical Engineers.

[22]Variation Simulation Analysis on-line help, Teamcenter Visualization 10.1.4, Siemens PLM Software

[23] NX CMM on-line help, NX 9.0.2.5, Siemens PLM Software

[24] Dimensional Planning and Validation Lite Foundation 1.0.2 Documentation, Teamcenter Visualization 10.1.4, Siemens PLM Software

[25] Olaf Sauer. Information Technology for the Factory of the Future – State of the Art and Need for Action, The 8th International Conference on Digital Enterprise Technology (DET2014), Stuttgart, Germany 2014

[26] Prof. Dr.-Ing. Bernd Scholz-Reiter. The Internet of Things – Threats and Opportunities of Improved Visibility, in *Architecting the Internet of Things* (ed. Dieter Uckelmann, Mark Harrison, Florian Michahelles). Springer Berlin Heidelberg, 2011. ISBN: 978-3-642-19156-5 (Print) 978-3-642-19157-2 (Online)